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Performance of Thin-Ceramic-Coated Combustion Chamber with
Gasoline and Methanol as Fuels in a Two-Stroke SI Engine

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ABSTRACT

The performance of a conventional, carbureted, two-stroke spark-ignition (SI) engine can be improved by providing moderate thermal insulation in the combustion chamber. This will help to improve the vaporization characteristics in particular at part load and medium loads with gasoline fuel and high-latent-heat fuels such as methanol. In the present investigation, the combustion chamber surface was coated with a 0.5-mm thickness of partially stabilized zirconia, and experiments were carried out in a single-cylinder, two-stroke SI engine with gasoline and methanol as fuels. Test results indicate that with gasoline as a fuel, the thin ceramic-coated combustion chamber improves the part load to medium load operation considerably, but it affects the performance at higher speeds and at higher loads to the extent of knock and loss of brake power by about 18%. However, with methanol as a fuel, the performance is better under most of the operating range and free from knock. Carbon monoxide (CO) emissions are significantly reduced, by about 3 to 4% volume, for both gasoline and methanol fuels due to relatively lean operation and more complete combustion. NO_x emissions were not measured. The results show that moderate thermal insulation of the two-stroke SI engine's combustion chamber is better suited to methanol fuel with respect to thermal efficiency, CO emissions, and knock-free operation compared to gasoline fuel.

TWO-STROKE SPARK-IGNITION ENGINES are lightweight, compact, and high specific power output prime movers. They are widely preferred for light-duty and portable equipment applications. However, the two-stroke engine's performance is limited by its poor scavenging characteristics. In the conventional, mixture-scavenged, two-stroke SI engine, it is reported that a considerable (15-40%) amount of the fresh charge is lost to the engine exhaust due to short-circuiting. This adversely affects both the fuel economy and hydrocarbon emission characteristics of the engine [1]. From the

combustion point of view, the two-stroke SI engine suffers from poor combustion efficiency and irregularity of combustion under light load applications because of the higher concentrations of residuals in the engine cylinder [2].

For the development of an efficient and less polluting two-stroke SI engine, research efforts are going on worldwide to achieve the following objectives:

1. Reducing fresh charge loss during the scavenging process; and
2. Improving the combustion process.

The engine combustion process is always central to the emissions and performance improvements, as is the case with two-stroke engine combustion. From a thermodynamic stand-point, it is difficult to achieve the constant volume requirement for better performance in two-stroke cycle operation due to the presence of large exhaust residual contents [3]. It is reported that in a burning mixture, the presence of residual gases reduces the speed of flame propagation, giving rise to unstable combustion [4]; this results in misfiring, which in turn leads to higher HC emissions and poor fuel economy [2]. To achieve smoothness in engine operation and to compensate for the fresh charge loss, rich mixtures are utilized. However, this results in higher CO emissions and other combustion-related problems due to poor vaporization of the fuel. It is thought that the difficulties of two-stroke engine combustion can be reduced more effectively through stabilized combustion of lean mixtures. This objective is difficult to attain unless improvements in the mechanism of the conventional combustion process within two-stroke cycle engines are possible [2,5]. This is an area where much effort is currently expended. In this regard, the following two attempts are worth mentioning:

1. Combustion improvement by proper control of gas flow, into the cylinder by Jo et al. [6], widely known as the NiCE process; and
2. Using the active thermo-atmosphere combustion (ATAC) process by controlling the ratio of mixture to residual gases and the mean charge temperature, by Onishi et al. [3].

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However, significant benefits are observed with these methods for only a narrow range of engine operation, and they have yet to establish their suitability for regular use.

The current type of gasoline fuel cannot exploit the potential advantages of lean combustion because of the rapid decrease in flame speed with leaner mixtures and its narrow flammability limits [7]. For relatively good lean combustion characteristics, methanol has been found to be a more suitable fuel compared to gasoline and other hydrocarbon fuels. Methanol has wider flammability limits and higher flame speeds under lean conditions than gasoline [8-11]. Methanol fuel's most desirable feature is its high research octane quality. Methanol rates 106-115 octane number by the research method and 88-92 octane number by the motor octane method. Methanol as the sole fuel will not cause any vapor lock in the carburetor. Because of these characteristics, methanol has been considered to be one of the most likely alternative automotive fuels in the foreseeable future.

Methanol has a heat of combustion half that of gasoline, but its latent heat of evaporation is nearly four times that of gasoline. This undesirable feature causes poor vaporization of the mixtures at part loads, with associated combustion problems. External heating of the mixtures has been suggested in the literature [12,13] to improve the vaporization characteristics, but it affects the volumetric efficiency. The complexity of the systems is an added disadvantage with two-stroke engines. On the other hand, in-cylinder modifications present a more attractive option compared to the use of external gadgets; the problems associated with combustion can be controlled at the source itself. In this respect, the concept of moderate thermal insulation of the combustion chamber has received consideration in recent engine research.

MODERATE THERMAL INSULATION OF THE COMBUSTION CHAMBER

The concept of thermal insulation of the combustion chamber has been more widely investigated in diesel engines [14-17] than in SI engines [18,19]. This approach is central to all low-heat-rejection engine development, both from the standpoint of materials and engine-component development and in terms of providing durability and strength at very high temperatures. Kobori et al. [20] and Amann [21] have discussed in detail the pros and cons of the low-heat-rejection concept in the context of diesel engines.

The primary interest in thermal insulation of diesel combustion chambers has been two fold: first, to reduce the size of, or to eliminate, the engine cooling system; and second, to improve engine efficiency. To these might be added the ability to burn lower-grade fuels because of the higher cylinder-gas temperatures attainable without cooling [20]. The application of thermal insulation in SI engines has been hampered by the possibility of charge autoignition and knock or preignition resulting from

increased component temperatures. Thus, the approach favored by many investigators has been to apply thick, plasma-sprayed ceramic coatings or a very high degree of insulation by air gap and/or nimonic materials. However, there are several disadvantages associated with use of thick thermal barrier coatings in insulated engines, such as poor mechanical reliability beyond 0.5 mm insulating thickness, deterioration of volumetric efficiency due to high combustion-chamber surface temperatures, and tribological problems; because of the knocking problem, this approach is limited to diesel engines. In some investigations [22,23], it is claimed that with thick insulation the heat flux increases (rather than decreases) due to very high surface temperatures affecting the engine performance adversely.

Roy Kamo et al. [24] investigated the merits of thin ceramic coatings of the order of 0.5-mm as against thick coatings of a few millimeters. Such coatings have been used satisfactorily in the gas turbine industry for the turbine blades, stator vanes, and combustion parts. Analytical studies, including transient heat-transfer effects, suggest that the surface cyclic temperature swings around the mean temperature in the same manner for both thin and thick coatings. This suggestion opened the possibility of employing thin thermal barrier coatings for gasoline engine application. Further, application of the thin ceramic coating to the combustion chamber of a gasoline engine would consistently provide the same level of insulation, regardless of the total operating hours of the engine and the type of fuel used.

The works of Assanis et al. [19,25,26] dealing with the use of thin ceramic coatings to improve the spark-ignited petrol engine's performance and emission characteristics are important, being among the few investigations available. They modified a 2.5 L, four-stroke SI GM engine with ceramic-coated pistons, liners, head, valves, and ports.

Thus, a thin ceramic coating applied to spark-ignition engines could be a useful means for improving the performance, fuel economy, and exhaust emissions. However, the degree of insulation is an important factor that needs to be ascertained from the view-point of knock-free performance of the engine.

CERAMIC COATING OF THE COMBUSTION CHAMBER

A suitable design is required to provide a moderate thermal insulation of the combustion chamber. This could be achieved either by (1) fixing an insert made of a low-thermal-conductivity material to the standard aluminum-silicon alloy piston and cylinder head or (2) coating the parent piston and cylinder head with low thermal-conductivity ceramic material. This material should have a coefficient of thermal expansion close to that of the aluminum-silicon alloy so that, for a given temperature increase, thermal stresses in the interface will

be minimal. Given such considerations, composite designs (with metal inserts and/or air gap, the thermal conductivity of which is less than that of the parent components) and thermal barrier coatings have been widely used. In comparison, the durability of ceramic coatings is less satisfactory than that of composite components. The advantage of the ceramic coating, however, is that it is easier to coat the combustion chamber with ceramic material than to produce composite components. Furthermore, engine components made from ceramic materials could have lower cost, improved dimensional consistency, and better wear characteristics than equivalent components made with conventional materials.

Among the various ceramic materials, partially stabilized zirconia (PSZ) has excellent toughness, hot strength, and thermal shock resistance, low thermal conductivity, and a thermal expansion coefficient close to those of steel and cast iron [27,28]. The properties of various ceramic materials and standard aluminum-silicon alloy materials are summarized in Tables 1 and 2, respectively. PSZ has been widely used as a thermal barrier coating in the combustion chambers of diesel engines. Hence, in the present work, PSZ was chosen as the material for the thermal barrier coating in the combustion-chamber walls.

In the present investigation, the piston top and cylinder head (combustion-chamber surface) were coated with the PSZ ceramic material, using a plasma spraying technique. Plasma spraying is a thermal spray process that uses an inert plasma stream of high velocity to melt and propel the coating material on to the substrate. First, the combustion-chamber surface was prepared with a wash coat of nickel-aluminum composite 100 microns (μm) thick for better bonding of the aluminum and PSZ material. PSZ with 8% yttria was deposited to a thickness of 400 μm over the wash coat material. The objective of

the present work is to examine the effect of a thin ceramic coating in the combustion chamber of a two-stroke SI engine with regard to engine brake thermal efficiency, combustion, and exhaust emission characteristics with gasoline and methanol as fuels.

EXPERIMENTAL PROGRAM

A single-cylinder, air-cooled, loop scavenged, carbureted two-stroke spark-ignition engine, the details of which are given (as Engine-1) in Table 3, was used for the experimental study. This engine was coupled to an eddy current dynamometer for speed and torque measurements. Calibrated standard instrumentation was used to measure fuel and air flow rates. The cylinder pressure was measured by a flush-mounted piezo-electric pressure transducer (Kistler). The cylinder pressure, crank angle, and spark signals were fed to a digital data-acquisition system (Iwatsu) for storage and subsequent analysis of various combustion parameters. Hydrocarbons (HC) (n-hexane equivalent) and carbon monoxide emissions were measured on a volume basis by an infrared gas analyzer (Horiba, Mexa 324FB). The exhaust sample was taken from a tap located close to the exhaust port. The sample was passed through a cold trap to prevent water vapor interference with the functioning of the infrared analyzer. Since the engine exhaust consists of a large percentage of unburned hydrocarbons, care was taken to prevent any condensation losses by providing a heater on the sample line to the exhaust analyzer. The exhaust gas analyzer was periodically calibrated, per the instructions of the manufacturer, using the calibration gas that was supplied with the instrument. The lubricating oil used was SAE30, mixed in the proportion by volume of 35 cc to 1000 cc of gasoline. Carburetor jet sizes having diameters of 0.98 to 0.80 mm were available for tests. However, a standard jet size of

Table. 1 Properties of Some Ceramic Materials [19,27,28,29]

Properties	Silicon Nitride		Syalon	Silicon Carbide		Alumina	PSZ
	RBSN	HPSN		SBSiC	HPSiC		
Density (10^3 kg/m^3)	2.3-2.7	3.1-3.2	3.2	3.1	3.0-3.3	3.3	5.8
Specific Heat (J/kg°C) @20°C	710	710	710	710	669	1172	54.3
@600°C				1087	1120		
Thermal Conductivity (W/m°C) 20°C	5-15	30	25	104	87	20	2.0
600°C				39	49		
Thermal Expansion Coeff. (10^{-6}K^{-1})	3.2	3.1	3.2	4.3	5.0	6.9	10.6
Bend Strength (MN/m ²)	200	800	800	500	750	450	610
Elastic Modulus (GPa)	170	290	300	375	430	360	200
Hardness (B)	1000	1800	2000	1860	2800	1600	1200
Thermal Shock Index	0.56	0.81	0.8	0.26	0.43	0.2	0.3
Thermal Cycle Index	2.4	13.5	15	16	12	0.8	0.5

Table 2. Properties of Al-Si Alloy and Niresist Materials

Mechanical Properties	Al-Si Alloy	Niresist
Tensile strength (MPa)	250	170
Hardness (HB)	110-135	120
Mean coefficient of Thermal expansion ($10^{-6}/^{\circ}\text{C}$)		
20/100 $^{\circ}\text{C}$	19.8	-
20/200 $^{\circ}\text{C}$	21.4	18.7
Density (10^3kg/m^3)	2.65	7.3
Thermal conductivity (W/m.K)	153 @175 $^{\circ}\text{C}$	40 @200 $^{\circ}\text{C}$
Specific Heat Capacity (J/kg.K)	960	500
Nominal Modulus of Elasticity-En value (GPa)	71	96.5

Table 3. Specifications of the Test Engines

Specifications	Engine 1	Engine 2
Make	BAJAJ	TVS
No. of Cylinders	One	One
Bore (mm)	57	41
Stroke (mm)	57	42
Displacement Volume (cc)	145.55	55.45
Compression Ratio	7.4:1	8:1
Rated Power (kW)	4.2 @5200 rpm	1.7 @5000 rpm
Cooling Medium	Air-cooled	Air-cooled
Mixture Induction	Rotary Disc System	Reed Valve
Scavenging System	Loop (Schnurle)	Loop Scavenging
Ignition System	Magneto-coil	CDI

0.84 mm was employed for the normal engine, based on the exhaust emission levels and air-fuel ratio (10.5 to 13.5). For methanol fuel operation, a jet size of 1.4 mm was employed to deliver the same output as that of normal gasoline fuel. Castor oil, 3.5% by volume, was added to the methanol fuel for lubrication.

Experiments were conducted with variable loads at constant engine speeds of 2000, 3000, and 4000 rpm with gasoline and methanol as fuels. Throughout the experiments, the ignition timing was maintained at MBT (minimum spark advance for best torque) settings. At each operating condition, dynamometer load, speed, fuel and air flow rates, cylinder pressure, dynamic spark timing signal, crank angle signal, and HC and CO emission readings were recorded after allowing sufficient time for the engine to stabilize. At each operating point, about 10-15 values of speed and torque were continuously recorded; averaging has been done to minimize the effects of variations. Similarly, fuel and air consumption rates were computed on an average basis. The pressure time, crank angle, and dynamic spark timing signals were averaged over 100 cycles. After calculating the performance parameters, a polynomial curve fitting (least square method) was employed to draw the mean curves. The deviation between the mean curve and data points was kept minimum.

RESULTS AND DISCUSSION

The effects of a thin ceramic coating on the combustion chamber of a small two-stroke SI engine with gasoline and methanol as fuels are discussed below with regard to engine brake thermal efficiency, exhaust emissions, knock, and combustion characteristics based on the basis of the present test results.

The performance characteristics of the thin-ceramic-coated combustion chamber, using gasoline and methanol as fuels, are depicted in Fig. 1 at constant engine speeds of 2000, 3000, and 4000 rpm. The results obtained with a normal combustion chamber, using gasoline as a fuel, are also presented for comparison. The ceramic-coated combustion chamber produced a considerable improvement in the brake thermal efficiency compared to the normal combustion chamber, with both gasoline and methanol as fuels, at all three speeds tested.

With gasoline as a fuel, the improvement in brake thermal efficiency is considerable at low to medium speeds and at part load to medium load. For instance, the maximum absolute brake thermal efficiency increases from 14.5% to 19.5% for the ceramic-coated combustion chamber over the normal combustion chamber at 1.5 kW, 2000 rpm; from 16.9 % to 20.5 % at 2.2 kW, 3000 rpm; and from 17.2 % to 19.5 % at 2.7 kW, 4000 rpm. These

Fig.1 Variation of brake thermal efficiency with brake power for PSZ-coated combustion chamber

improvements are attributable to the better vaporization characteristics of the rich mixtures in the moderately raised combustion chamber temperature, which in turn results in more complete combustion. Two-stroke SI engines are normally supplied with rich mixtures (Fig. 2) to compensate for the loss of fresh charge and exhaust dilution effects. This results in a heterogeneous mixture, and much of the fuel is carried to the engine in the form of large droplets, in particular at part load and low speed. Under these conditions, a considerable quantity of heat is required to completely vaporize the fuel. External heating of the rich mixtures improves vaporization characteristics, but it adversely affects the trapped charge density. Providing a hot combustion chamber will result in complete vaporization of the rich mixtures. This hot combustion chamber can be obtained by providing moderate thermal insulation (such as a thin ceramic coating) in the combustion chamber, to retain the heat generated from combustion. With the thin-ceramic-coated combustion chamber, higher brake thermal efficiencies were obtained at part load to medium load at all three speeds tested. However, at higher speeds, the brake power of the ceramic-coated combustion chamber drops off by as much as 18% at 4000 rpm (from 3.81 kW to 3.15 kW).

The performance deterioration at higher speeds and at higher loads is partly attributed to the drop in delivery ratio, which in turn lowers the density of the trapped charge associated with the relatively hot combustion-chamber environment. The variation of delivery ratio with brake power is illustrated in Fig. 3 for ceramic-coated and normal combustion chambers at wide open throttle (WOT). It is evident that there is a drop in the delivery ratio with the ceramic-coated combustion chamber with respect to the normal combustion chamber at WOT conditions. Similar results, indicating a drop in performance at higher speeds with the insulated combustion chamber, were also reported by Assanis [19] for a 2.5-L, four-stroke SI engine.

Further, at 4000 rpm, the brake output is limited by the onset of knock. One would expect the insulated combustion chamber to promote knock due to the higher surface temperatures associated with the combustion chamber; however, no such tendency was observed during these studies at low and medium speeds. But a knock was noticed and identified by the pressure-time trace at 4000 rpm, as is discussed later. This drawback raises serious questions about the application of the concept of a thin-ceramic-coated combustion chamber in a gasoline engine. Hence, it is cautioned that the degree of insulation (thickness of ceramic coating and properties of ceramic material) plays an important role in achieving the desired results, and it needs to be optimized with regard to knock and brake power.

An alternative design for moderate thermal insulation of the combustion chamber was developed to eliminate the knock and loss of brake output at higher

Fig.2 Variation of air-fuel ratio with brake power for normal engine with gasoline as a fuel

Fig.3 Comparison of delivery ratio over engine speeds at WOT condition for PSZ-coated combustion chamber

loads and at higher outputs. In this case, the normal aluminum alloy piston and cylinder head were provided with a cap made of niresist material (a form of cast iron with high nickel content). A 0.5-mm air gap was also provided underneath this cap. The construction of the composite piston and cylinder head is shown in Fig. 4. Niresist material has a thermal expansion coefficient of the same order as that of aluminum alloy, and it has a much lower thermal conductivity than aluminum. The properties of niresist materials are compared with standard aluminum-silicon alloy materials in Table 2. Care was taken to see that the overall dimensions of the piston and cylinder head were maintained at their original values. As a result of niresist inserts on both piston and cylinder head, the composite piston and cylinder head are relatively heavier compared to the parent components, mainly due to mechanical fixtures. However, a suitable casting method would eliminate these mechanical fixtures

Fig.4 Piston and Cylinder Head Insulated by Niresist Inserts

and bring the weight of the composite components closer to the original values. These two types of insulated combustion chambers, viz., composite components and ceramic-coated components, were tested in a single cylinder, two-stroke SI engine of 55 cc displacement volume. The details of this Engine 2 are listed in Table 3. The variation of brake thermal efficiency with brake power for both the insulated combustion chambers operating on gasoline fuel are presented in Fig. 5 at constant engine speeds of 3000 and 4500 rpm. The detailed results for all test conditions with gasoline and methanol fuels are discussed elsewhere [29,30]. It is evident from Fig. 5 that the composite components produce a consistent improvement at both low and high speed and load conditions, compared with the ceramic-coated components. The maximum percentage improvement in the brake thermal efficiency is about 15.4% at 0.8 kW, 3000 rpm and about 11.4% at 1.1 kW, 4500 rpm,

Fig.5 Variation of brake thermal efficiency with brake power for composite piston-head and PSZ-coated combustion chambers

respectively, for the composite components compared to the normal combustion chamber. However, with the ceramic-coated combustion chamber, the maximum improvement in the brake thermal efficiency is about 9% at 0.8 kW, 3000 rpm and only marginal at 4500 rpm, compared to the normal combustion chamber. It is evident that the performance improvement of the ceramic-coated combustion chamber is less significant than that for the composite-component combustion chamber, in particular at higher outputs and at higher speeds, due to mild knock and loss of brake power. Further, the composite components are free from either preignition or knock in the entire range of engine operation, and the loss of output at higher outputs is negligible. These advantages of composite components are mainly

attributable to the more uniform insulation, freedom from hot spots and, possibly, safe insulation degree (knock-free operation) of the composite components compared to the ceramic-coated components. It is also possible that the high nickel content in the niresist inserts in the composite-component combustion chamber provide better durability in the case of knock [31] in prolonged operations. To understand the differences in thermal behavior between the ceramic-coated combustion chamber and composite components, a high-resolution, time-dependent heat-transfer analysis is essential, but this is beyond the scope of the present work.

With methanol as a fuel, the ceramic-coated combustion chamber improves brake thermal efficiency considerably over the entire test range of engine operation. The improvements obtained are qualitatively in line with those obtained with gasoline fuel at part load to medium load and at slow speed to medium speed. For instance, the absolute maximum brake thermal efficiency increases from 14.5% to 20.8% at 1.45 kW, 2000 rpm; from 16.9% to 21.7% at 2.2 kW, 3000 rpm; and from 17.2% to 20.68% at 2.75 kW, 4000 rpm. The methanol fuel's undesirable characteristics, such as poor vaporization at part load and associated combustion problems, were eliminated to a great extent with the insulated combustion chamber. Even at full load and at higher speeds, the performance is much better compared to both normal and ceramic-coated combustion chambers with gasoline as a fuel. The delivery ratio characteristics are also superior compared to gasoline fuel at WOT conditions, as shown in Fig. 3. The usual problems associated with the insulated combustion chambers, such as a drop in delivery ratio, were also negligible for a combustion chamber with moderate thermal insulation operating on methanol fuel.

Figure 6 shows the comparison of delivery ratio between the normal combustion chamber with gasoline fuel and the ceramic-coated combustion chamber with methanol fuel at 4000 rpm. It is evident from this figure that higher delivery ratios are obtained with methanol fuel than with gasoline fuel. This is the case because methanol fuel's higher latent heat of vaporization cools the air entering the engine much more than does gasoline, thus increasing the air density and mass flow. Apparently, the low thermal inertia of the thin ceramic coating ensures that the ceramic component's surface responds to the gas temperature transients faster than in the metal engine. As a result, heat transfer from the walls to the gas during intake and compression is reduced compared to the metal engine; this results in improved delivery ratio, and thus a higher brake output, for the ceramic-coated combustion chamber. At WOT conditions, the brake output increases from 1.7 kW to 2.1 kW at 2000 rpm and from 3.15 kW to 3.35 kW at 3000 rpm. At higher speeds and at higher outputs, the maximum brake output is nearly the same as that of a normal gasoline engine, and the engine is free from knock. It is evident from these results that the hot environment in the ceramic-coated combustion chamber is effectively utilized to vaporize the high-latent-heat methanol fuel.

Fig.6 Variation of delivery ratio with brake power for PSZ-coated combustion chamber with methanol

Fig.7 Variation of equivalence ratio with brake power for PSZ-coated combustion chamber

Figure 7 compares the variation of fuel-air equivalence ratio with brake output between the normal combustion chamber and the ceramic-coated combustion chamber with methanol fuel. The results suggest that methanol has better lean combustion characteristics in the insulated combustion chamber compared to the normal combustion chamber operating on gasoline fuel. The high octane value of the methanol fuel was an added advantage; the engine operated quite smoothly over its entire range without any knock. Therefore, the combination of a hot combustion chamber with the high latent heat of evaporation, wide flammability limits, higher flame speeds, high octane value, and relatively better lean combustion characteristics of methanol fuel gave significant improvements compared to normal gasoline fuel in a thin-ceramic-coated combustion chamber.

After about 20 hours of engine testing, it was observed that the ceramic coating was intact, with no appreciable wear. Also, deposit formation over the ceramic coating was minimal. It is expected that moderate thermal insulation of the combustion chamber would prevent uncontrolled buildup and subsequent growth of deposits due to the relatively hot surface. Hence, it could also minimize knock problems associated with deposits over time. A limited, 50-hour, endurance test that was carried out also revealed that the insulation provided by composite components was stable. There was no appreciable wear or deposit formation over the composite components.

The two-stroke SI engines employed in the present investigation were carbureted and widely preferred in motorcycles, mopeds, and auto-rickshaws (two- and three-wheeled vehicles). An estimated 10 million vehicles with two-stroke SI engines are currently employed in India [29]. However, it has been recognized that the automotive two-stroke SI engines are fuel-injected and are subjected to higher thermal stresses and gas temperatures than in the case of carbureted two-stroke SI engines. Hence, the results of this study may not necessarily apply for fuel-injected, two-stroke SI engines.

In comparison, with gasoline as a fuel, the thin-ceramic-coated combustion chamber improves the part-load and slow-speed operation, but it adversely affects the performance at higher speeds and at higher loads, producing knock and considerable loss of brake power. However, with methanol as a fuel, the performance is better under most of the operating conditions and free from knock. Further, it is possible to operate with lean mixtures under the moderately raised combustion-chamber temperatures.

Further insight into the performance of the thin-ceramic-coated combustion chamber with gasoline and methanol as fuels can be provided through the exhaust gas analysis. Issues related to pollution formation in a thin-ceramic-coated combustion chamber are still unclear. The exhaust emission levels in the ceramic-coated engine could be different than in the normal engine due to mixture changes, the different character of combustion, and dissociation at higher operating temperatures. Figure 8 shows the CO emission levels at constant engine speeds of 2000, 3000, and 4000 rpm. These results indicate that the ceramic-coated combustion chamber lowers CO emissions considerably, with both gasoline and methanol as fuels, compared to the normal combustion chamber operating on gasoline fuel. With gasoline as a fuel, the maximum reduction in CO emission is about 3.7% vol. at 1.7 kW, 2000 rpm; 3.4% vol. at 2 kW, 3000 rpm; and 3% vol. at 2.2 kW, 4000 rpm. With methanol fuel, the maximum reduction in CO emission is about 6% vol., 3.45% vol., and 3% vol., respectively, for the insulated combustion chamber over the normal engine at similar operating conditions. At 3000 and 4000 rpm, the CO emissions are less than 0.5% vol. over the entire load range with the insulated combustion chambers, for both gasoline and methanol as fuels. These substantial reductions in CO emissions are obtained mainly due to

Fig.8 Variation of carbon monoxide emissions with brake power for PSZ-coated combustion chamber

relatively lean operation (as depicted in Fig. 7) with the insulated combustion chamber compared to the normal engine. Also, moderate thermal insulation of the combustion chamber provides better vaporization of fuel and better utilization of air. The moderate insulation presumably increases the temperature of the burning gas, resulting in more complete, faster combustion. It is believed that the wide flammability limits and better lean burning characteristics of methanol in the relatively hot combustion chamber would make the combustion more complete, resulting in lower CO emissions.

A conventional two-stroke SI engine emits large amounts of hydrocarbons in the engine exhaust compared to its four-stroke counterpart. These unburned hydrocarbons in the exhaust arise from mixture short-circuiting, combustion of a fuel-lubricant blend, trapping of unburned charge in the crevices, and flame quenching [32]. With a moderate rise in the combustion-chamber surface temperature, flame quenching effects are minimized as the walls follow the gas temperatures; also, as a result of better combustion, the hydrocarbon concentration is reduced in the exhaust. These reductions in HC emissions for the insulated combustion chamber are shown in Fig. 9. The maximum reduction in HC emissions is about 420 ppm at 0.9 kW, 2000 rpm; and 2600 ppm at 3.1 kW, 3000 rpm for gasoline fuel. With methanol fuel, the reduction in HC emissions is about 600 ppm and 1900 ppm at similar operating conditions, respectively, compared to the normal engine. Nevertheless, a small increase (by about 50-100 ppm) in HC emissions was observed with the insulated combustion chamber at 4000 rpm. This marginal increase in HC emissions was probably due to breakup of the lubricating oil film, leading to higher hydrocarbon emissions, at higher combustion-chamber surface temperatures. Further, it may be noted here that the experimental measurements for comparison were obtained using a NDIR technique, since this was the only equipment available for the measurement in the author's laboratory. It is currently recognized that for an engine operating on gasoline/methanol, the flame ionization detector (FID) technique is more appropriate for measuring total hydrocarbon emissions. Nevertheless, the NDIR approach gives n-hexane equivalent hydrocarbon emissions in the absence of an FID. Many researchers [33-35] have suggested the use of multipliers, in the range of 1.7 to 2.3, to account for the partial measurements from the NDIR technique. However, the exact multiplier should be derived from both the methods for a given set of instruments and the range of HC concentration. In the absence of such a facility, the exact value of a multiplier is difficult to determine for representing total hydrocarbons. The author believes that the present approach is reasonable for demonstrating the qualitative trends of the HC emission levels for both gasoline and methanol fuels in the ceramic-coated combustion chamber. Further experimental work is recommended in order to obtain a more accurate quantitative assessment of the hydrocarbon emissions in the insulated combustion chamber.

Fig.9 Variation of hydrocarbon emissions with brake power for PSZ-coated combustion chamber

Owing to the equipment constraints, it was not possible to measure nitrous and nitric oxide (NO_x) emissions. The NO_x emissions, which increase with the bulk gas temperature, would tend to rise within an insulated combustion chamber. NO_x emissions are also expected to be higher with lean mixture operation. However, two-stroke engines generally emit lower NO_x emissions as a result of their large exhaust gas dilution [1,4], so it is believed that the increased NO_x emissions due to insulation are likely to be much lower than those of the equivalent four-stroke SI engine.

The variation of cylinder peak pressure at constant engine speeds of 2000, 3000, and 4000 rpm for both gasoline and methanol fuels with the thin-ceramic-coated combustion chamber is presented in Fig. 10. Cylinder peak pressures are higher with the ceramic-coated combustion chamber for both gasoline and methanol fuels compared to the normal combustion chamber operating on gasoline fuel. The improvement is considerable at low and medium speeds for gasoline fuel. For instance, the cylinder peak pressure increases from 17.1 to 23.1 bar at 2000 rpm and from 22.8 to 25.7 bar at 3000 rpm at WOT conditions, because the combustion-chamber surface initiates the preflame reactions faster and helps to burn the mixtures more completely, with the result that flame velocity is also higher. Hence, higher cylinder pressures were obtained. However, at 4000 rpm, with full-load operation, a slight knock was noticed and was confirmed by the pressure-time trace, as shown in Fig. 11. One would expect the ceramic-coated engine to exhibit knock or preignition, owing to the hot spots at elevated temperatures in the combustion chamber. However, the preignition phenomenon was not encountered during the entire testing period. It is also evident from the differentiated pressure-time trace (Fig. 11) that the knock was caused by end-gas auto-ignition rather than by the preignition source. In the first place, the coatings were very thin and therefore could not cause an appreciable increase in the mean cylinder temperature. In addition, the higher temperature swings in the ceramic-coated engine [25] could, to some extent, offset the temperature rise caused by the insulating effect during the later parts of compression, thus reducing the chance for preignition. With methanol as a fuel, the increase in cylinder pressure is consistent and significant over the entire range of engine operation. At WOT operating conditions similar to those noted above, the cylinder peak pressure increases from 17.1 to 23.8 bar at 2000 rpm and from 22.8 to 27.9 bar at 3000 rpm with the ceramic-coated combustion chamber operating on methanol fuel. Even at 4000 rpm and WOT condition, the cylinder peak pressure increases from 18.6 bar to 24.72 bar compared to the normal engine. These significant improvements presumably are obtained due to better utilization of the hot combustion chamber to vaporize the fuel mixtures, better preflame reactions, and better combustion. The moderate insulation increases the temperature of the burning gas, facilitating more complete and faster combustion of the charge. In addition to the better lean combustion capability, the high octane value of methanol fuel is an

Fig.10 Variation of cylinder peak pressure with brake power for PSZ-coated combustion chamber

Fig.11 Pressure, differentiated pressure-crank angle for the knock cycle with ceramic-coated combustion chamber

added advantage to run the engine smoothly and free from knock. If hot spots arise in the ceramic-coated combustion chamber during prolonged operation at higher speeds and at higher loads, the superior surface ignition characteristics of the methanol fuel will assist combustion as a multiple-ignition source in such situations (rather than leading to preignition or knock), unlike gasoline fuel (which usually leads to either preignition or knock).

The ignition delay and combustion duration characteristics obtained with the ceramic-coated combustion chamber for both gasoline and methanol fuels are presented in Figs. 12 and 13, respectively. From Fig. 12, it is evident that ignition delay is considerably reduced with the ceramic-coated combustion chamber, compared to the normal engine, for both the fuels. The reduction in ignition delay is about 2 to 6° CA for gasoline fuel and about 2 to 10° CA for methanol fuel at various operating conditions. Similarly, the combustion duration is also relatively shorter for both the fuels over that in the normal engine. The reduction in ignition delay and combustion duration are attributable to the better preflame reactions, and higher flame propagation velocities are due to the higher temperature of the burning gas with the ceramic-coated combustion chamber. The wide flammability limits and higher flame propagation velocities of methanol fuel under lean mixture conditions in the hot combustion chamber helps to lower the ignition delay and combustion duration in the entire range of engine operation. To understand the complete combustion behavior of a thin-ceramic-coated combustion chamber with gasoline and methanol fuels, further in-cylinder combustion measurements are recommended.

Fig.12 Variation of ignition delay with brake power for PSZ-coated combustion chamber

Fig.13 Variation of combustion duration with brake power for PSZ-coated combustion chamber

CONCLUSIONS

On the basis of the present experimental investigations with a thin ceramic coating on the combustion chamber of a two-stroke SI engine, with gasoline and methanol as fuels, the following conclusions are drawn:

1. A thin ceramic coating on the combustion chamber of a two-stroke SI engine has beneficial effects with regard to CO emissions due to leaner fueling. These improvements are significant, particularly at part loads and at low to medium speeds with gasoline fuel and over the entire test range for methanol fuel. With the insulated combustion chamber, fuel vaporization is expected to be better, which results in better combustion, lower combustion heat-transfer losses, fewer gas-to-wall heat interchanges, and lower flame quenching effects.
2. With gasoline as a fuel in the thin-ceramic-coated combustion chamber, the absolute brake thermal efficiency increases from 14.5% to 19.5% at 1.5 kW, 2000 rpm; from 16.9% to 20.5% at 2.2 kW, 3000 rpm; and from 17.2% to 19.5% at 2.7 kW, 4000 rpm over that for the normal engine. However, at high outputs and at high speeds, the brake power drops off by as much as 18% and is limited by knock. With methanol fuel, the improvement in brake thermal efficiency is similar to that of gasoline at part load to medium load and speed range, in addition to its superior performance at higher outputs. These improvements are attained, in part, because it is possible to operate lean mixtures with methanol fuel in a thin-ceramic-coated combustion chamber quite smoothly and without knock.
3. Carbon monoxide emissions are significantly reduced, by about 3 to 4% by volume, with the ceramic-coated combustion chamber for both gasoline and methanol fuels; this occurs because of the relatively lean mixture operation and better combustion due to the hot combustion-chamber environment. HC emissions are lower by about 400 to 2000 ppm in the part-load to medium-load range for both the fuels, presumably due to the lower flame quenching effects and complete combustion with the insulated combustion chamber.
4. Cylinder peak pressures are higher by about 4 to 6 bar with the ceramic-coated combustion chamber at 2000 and 3000 rpm, for both the fuels, under wide-open-throttle conditions. However, with gasoline, the peak pressure drops at high output and at high speed due to knock, which is confirmed by the pressure-time traces. With methanol, cylinder peak pressures are consistently higher over the entire range of engine operations compared to those for the normal engine.

5. Ignition delays are generally lower, and combustion duration is relatively shorter, with the ceramic-coated combustion chamber, in particular with methanol fuel (presumably due to its wide flammability limits and higher flame propagation velocities under lean mixture conditions). Also, the hot combustion chamber helps to increase the temperature of the burning gas, facilitating more complete and faster combustion of the charge.
6. In comparison, the thin-ceramic-coated combustion chamber is better suited for high-latent-heat fuels, such as methanol, to obtain the potential benefits with regard to engine thermal efficiency, CO emissions, lean combustion capability, and knock-free operation compared to gasoline. With gasoline fuel, these improvements are considerable during part-load to medium-load and speed-range operations but are affected by the loss of power output and knock at high outputs. However, a suitable design for the moderate thermal insulation, such as niresist inserts on both piston and cylinder head, will eliminate these drawbacks.

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